University College London

# Non-Standard Mechanisms for Neutrinoless Double Beta Decay

Frank Deppisch
f.deppisch@ucl.ac.uk

University College London

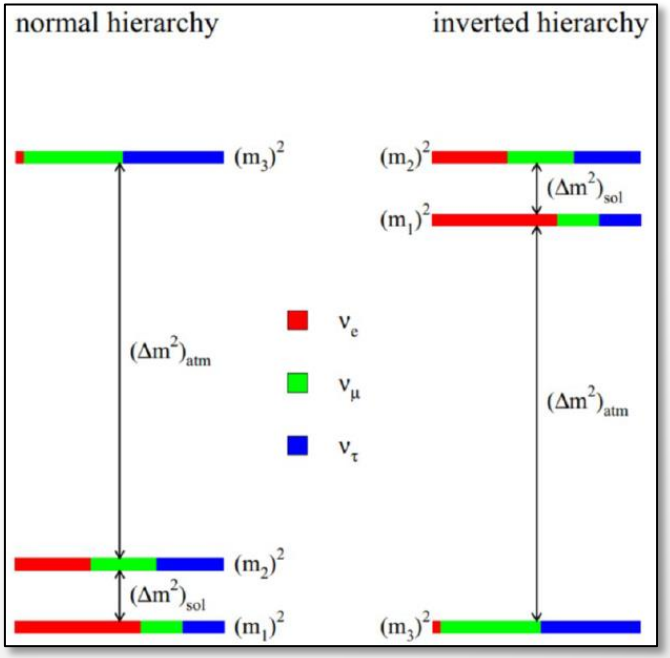
TAUP 2013 | Asilomar | 08-13/09/2013

# Neutrino Oscillations

University College London

- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation

$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$




- Solar Neutrino Oscillations
  - Large Mixing
- Atmospheric Oscillations
  - $\approx$ Maximal Mixing
- Reactor and Accelerator Neutrinos
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.021$
- Experimental Unknowns and Anomalies
  - CP Violation? Sign of $\Delta m_{23}$? Sterile Neutrinos?

# Absolute Neutrino Mass

University College London

- Energy Endpoint in Beta Decay

$$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_{\nu_i}^2 < (2.2\ \mathrm{eV})^2$$

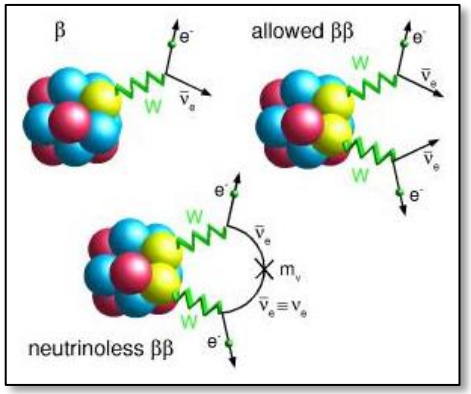
$\approx (0.2\ \mathrm{eV})^2$ (KATRIN, 2018)

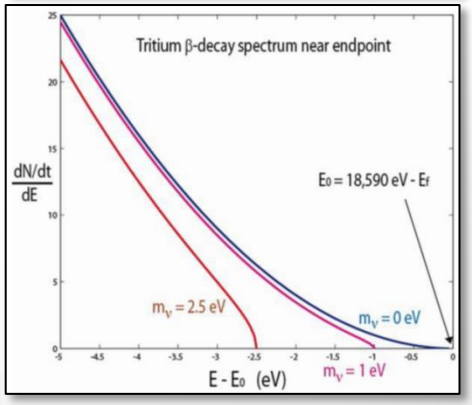
- Neutrinoless Double Beta Decay

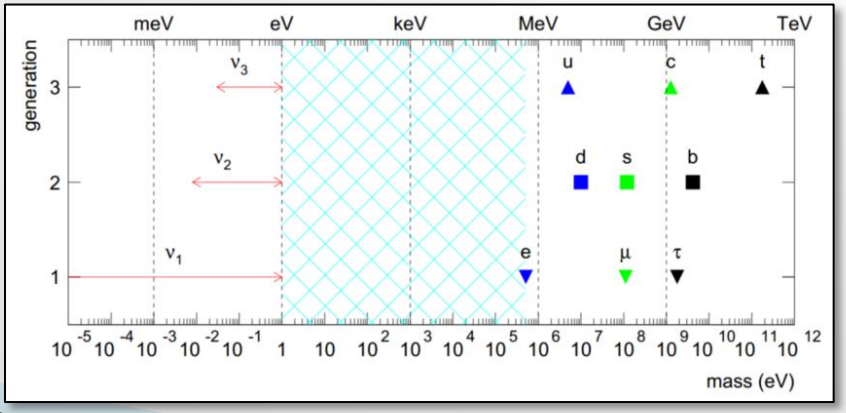
$$m_{\beta\beta} = |\Sigma_i U_{ei}^2 m_{\nu_i}| < 0.2 \cdots 1.0\ \mathrm{eV}$$

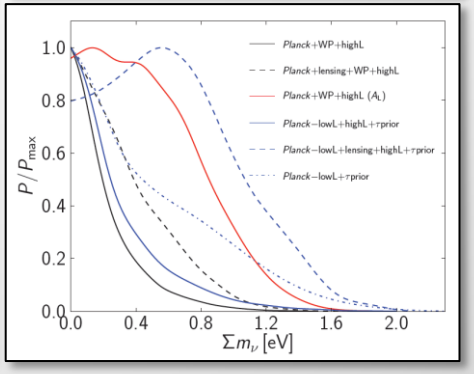
- Impact on Large Scale Structure

$$\Sigma = \Sigma_i m_{\nu_i} < 0.3 \cdots 1.0\ \mathrm{eV}$$



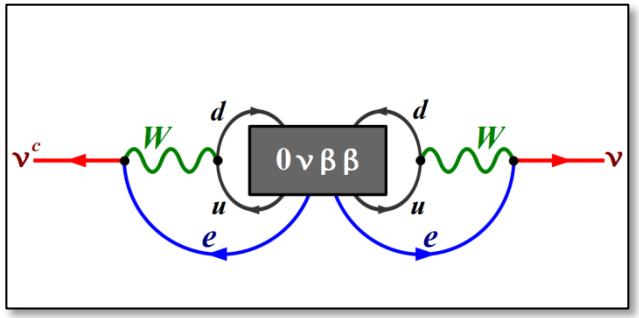



# Neutrinoless Double Beta Decay

University College London

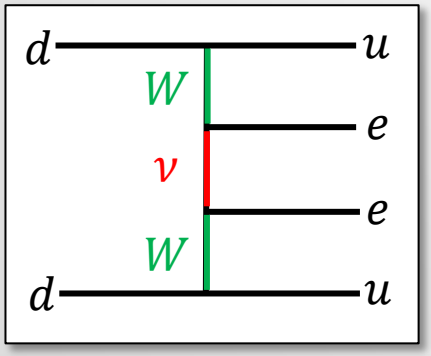
- Process $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- Uncontroversial detection of $0\nu\beta\beta$ of utmost importance
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles
    ("Black Box Theorem", Schechter & Valle '82)




$$\delta m_\nu \approx \frac{1}{(16\pi^2)^4}\frac{\mathrm{MeV}^5}{M_W^4} \approx 10^{-23}\mathrm{eV}$$

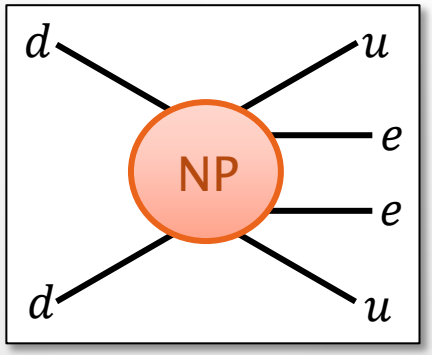
- Which mechanism triggers the decay?

Light Neutrino Exchange




$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\ \mathrm{yr} \rightarrow m_{\beta\beta} \approx 0.1\ \mathrm{eV}$$

General Effective Operator



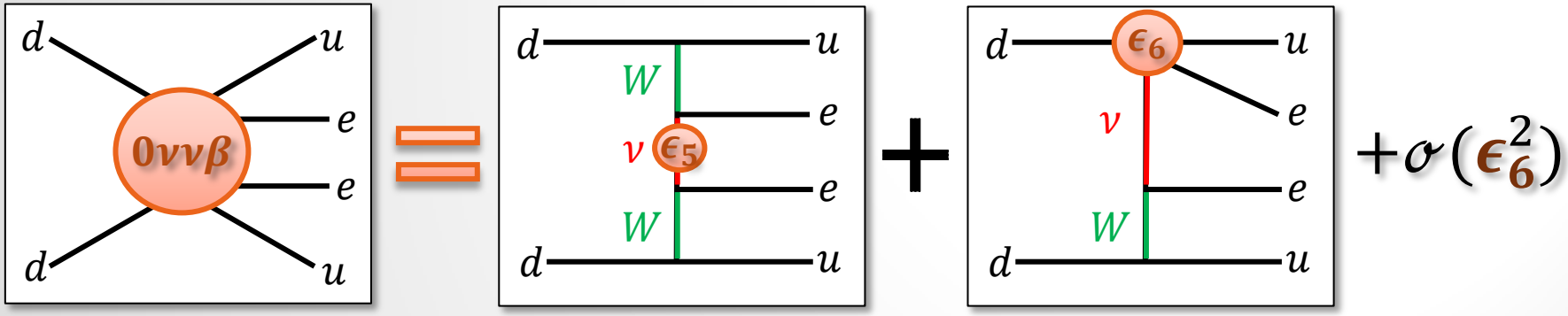

$$\frac{\bar{u}\bar{u}\bar{e}\bar{e}dd}{M_{LNV}^5}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\ \mathrm{yr} \rightarrow M_{LNV} \approx 1\ \mathrm{TeV}$$

# Effective $0\nu\beta\beta$ Operators

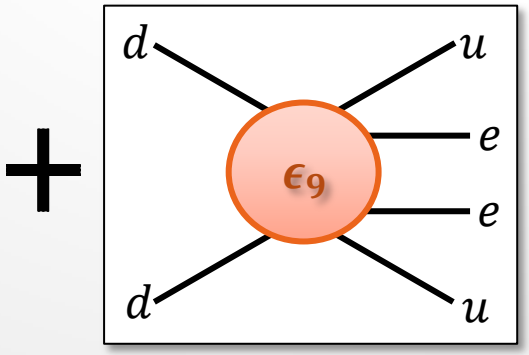
University College London

- Lorentz-Invariant Expansion in Effective Couplings
  (Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko '99, '00)




- Summation over leptonic $j$ and hadronic $J$ current combinations
  $(V \pm A, S \pm P, T_{L,R})$

$$\mathcal{L} = \frac{G_F}{2} j^{\mu}_{V-A} J^{+}_{V-A,\mu} + \frac{G_F}{2} \sum_i \epsilon^i_6 \, j \, J^+ + \frac{G_F^2}{2m_p} \sum_i \epsilon^i_9 \, j \, J \, J$$



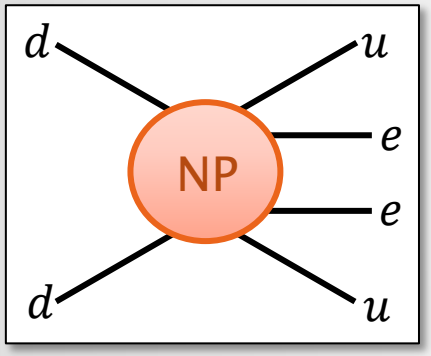

- Current $0\nu\beta\beta$ Limits (see FFD, Hirsch, Pas '12)

$$\epsilon^i_{6,9} \lesssim 10^{-9} \div 10^{-7}$$

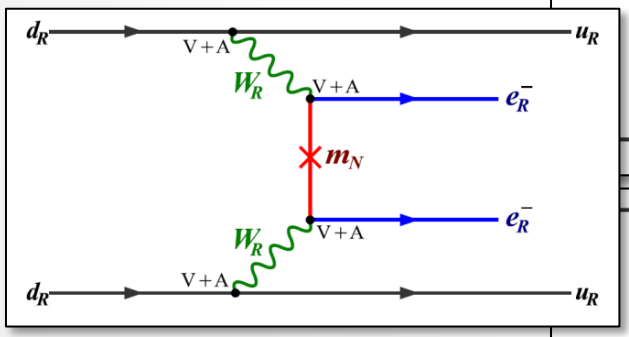
# New Physics Contributions to $0\nu\beta\beta$

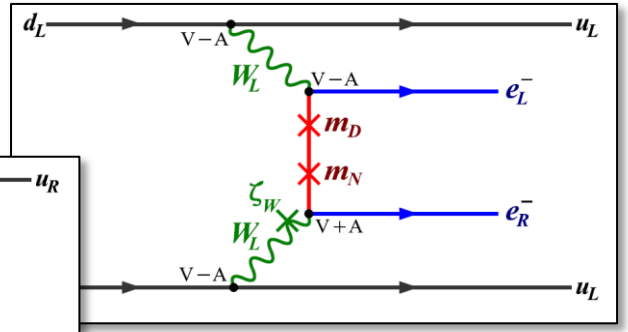
University College London

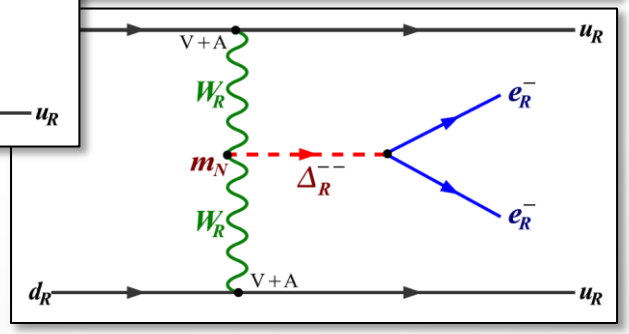
- Plethora of New Physics scenarios



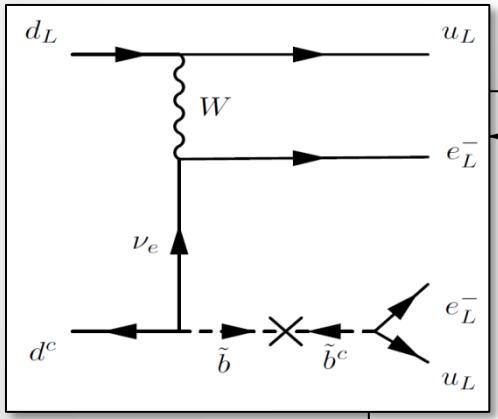

$$\Gamma = T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

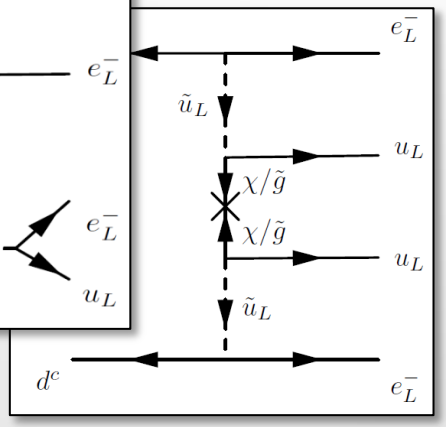



Left-Right Symmetry




R-Parity Violating SUSY

Extra Dimensions

(Majorons)

Leptoquarks

…

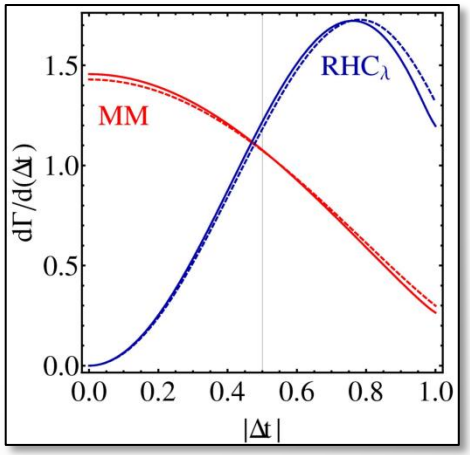
# Disentangling New Physics Contributions

University College London

- Angular and energy distribution of emitted electrons
  (Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

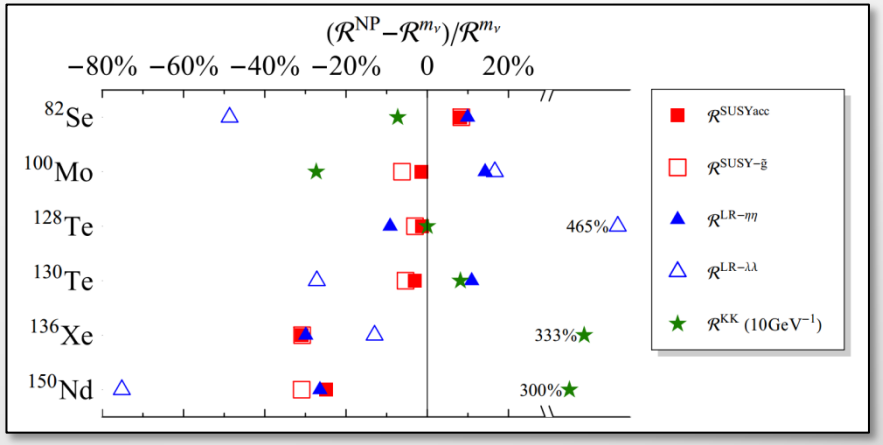
$$\frac{d\Gamma}{dE_{e_1}dE_{e_2}d\cos\theta} = \frac{\Gamma}{2}\left(1 - k(E_{e_1}, E_{e_2})\cos\theta\right), \qquad -1 < k < 1$$

  - Linear in $\cos\theta$
  - $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta\beta$ mechanism




- Comparison of $0\nu\beta\beta$ in multiple isotopes
  (FFD, Päs PRL 2007, Meroni et al. 2013)
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics
    (if one mechanism dominates)
  - See talk by Aurora Meroni tomorrow

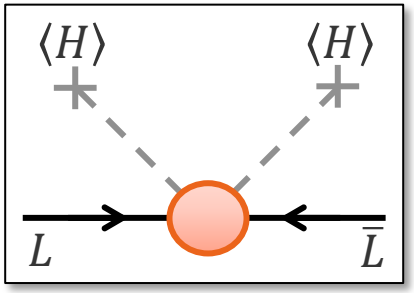
$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



# Effective Mass and Seesaw

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

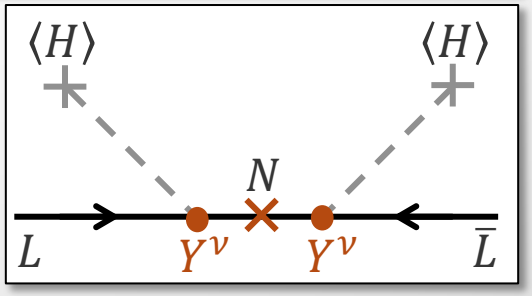



- Seesaw Mechanism
  - Add right-handed neutrinos $N_i$ to SM, $M_N \approx 10^{14}$ GeV

$$\mathcal{L} \supset Y_{ij}^\nu \bar{N}_i L_j \cdot H - \frac{1}{2}M_{ij}\bar{N}_i N_j^c \xrightarrow[\mu \ll M_N]{} \frac{1}{2}(Y_{ki}^\nu M_{kl}^{-1} Y_{lj}^\nu)(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right)$$

- Light neutrino mass

$$m_\nu \approx 0.1\ \text{eV}\left(\frac{Y_\nu \langle H \rangle}{100\ \text{GeV}}\right)^2 \left(\frac{10^{14}\ \text{GeV}}{M}\right)$$

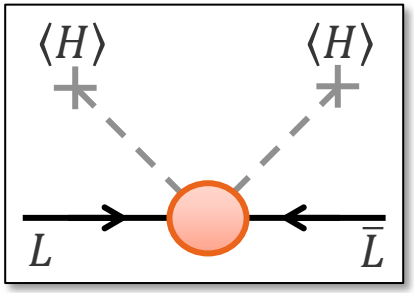


# Effective Mass and Seesaw

University College London

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

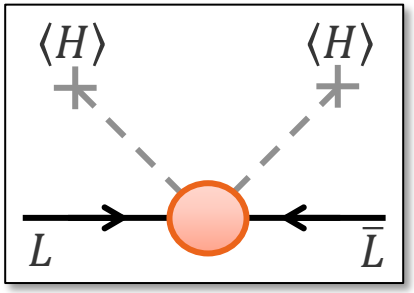



- Seesaw Mechanism
  - Sterile Neutrino Mass Scale Unknown
    - $\approx 10^{14}$ GeV — Naïve Seesaw, GUTs
    - $\gtrsim 10^{9}$ GeV — Thermal Leptogenesis
    - $\approx 10^{2}$ GeV — Resonant Leptogenesis, Production at LHC
    - $\approx 1$ keV — Dark Matter Candidate
    - $\approx 1$ eV — Oscillation, Cosmology, $0\nu\beta\beta$

# Effective Mass and Seesaw

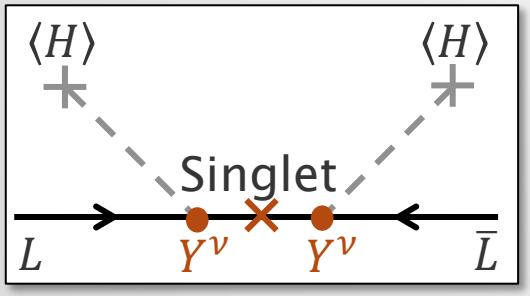
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

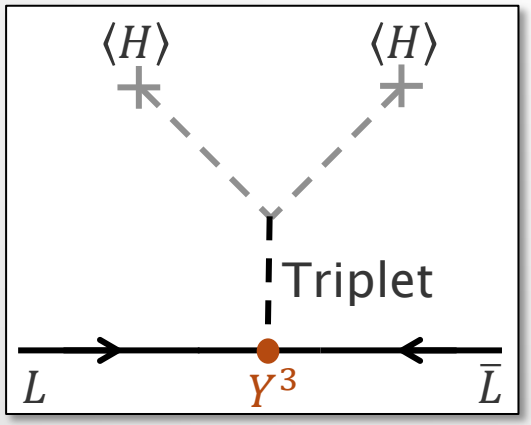



- Seesaw Mechanism
  - Three possible mediators at tree level

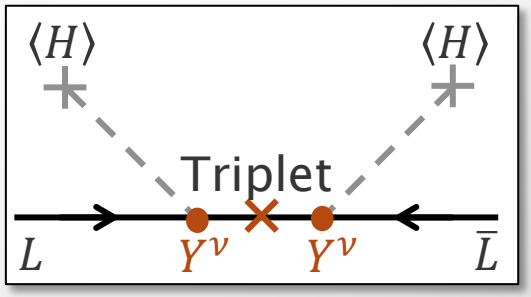
Seesaw I




Seesaw II



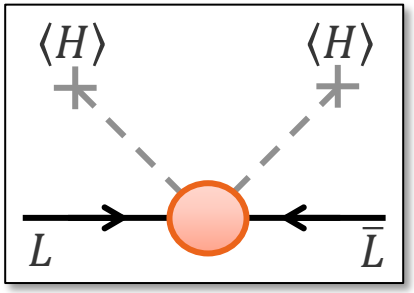

Seesaw III



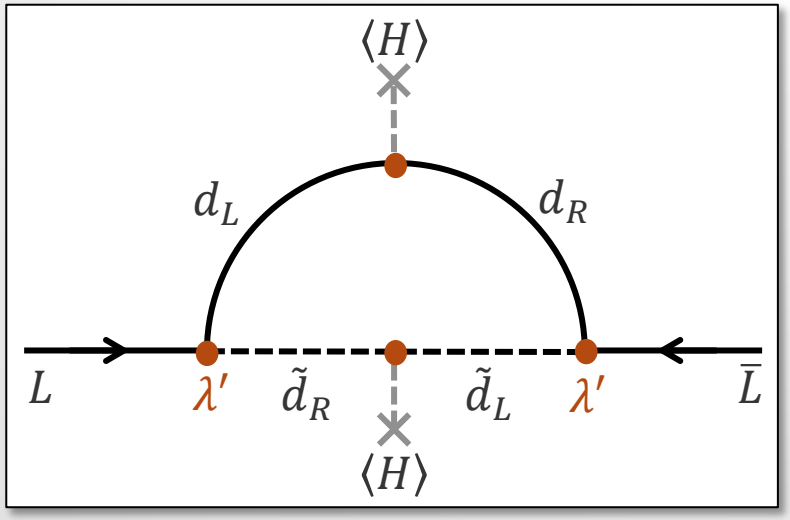
# Effective Mass and Seesaw

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)(H^T \cdot L_j) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$




- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. R-Parity Violating SUSY



# Problems of Naïve Seesaw

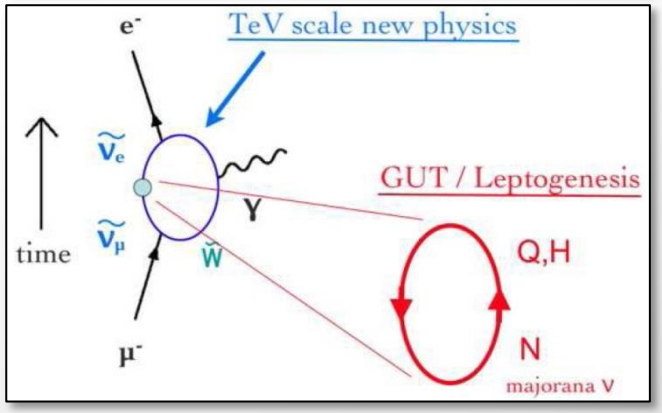
University College London

- Introduces high energy scale
- Right-handed neutrinos are singlets
  - Couple only via small mixture with active neutrinos
- Mechanism not testable with low energy observables

# Problems of Naïve Seesaw

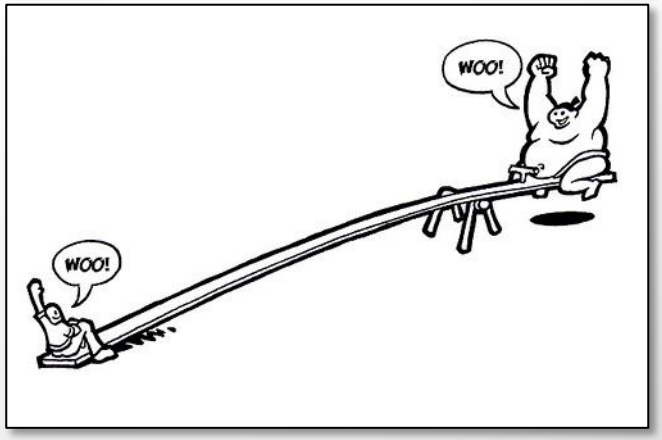
University College London

- Introduces high energy scale
- Right-handed neutrinos are singlets
  - Couple only via small mixture with active neutrinos
- Mechanism not testable with low energy observables
- Possible Solutions
  - SUSY Seesaw
    - Testable LFV effects from sleptons



# Problems of Naïve Seesaw

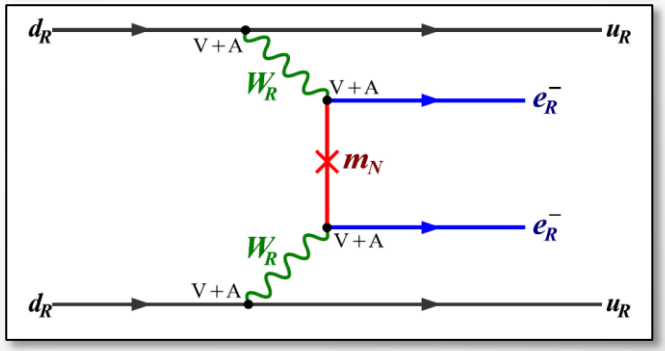
- Introduces high energy scale
- Right-handed neutrinos are singlets
  - Couple only via small mixture with active neutrinos
- Mechanism not testable with low energy observables
- Possible Solutions
  - SUSY Seesaw
    - Testable LFV effects from sleptons
  - "Bent" Seesaw mechanisms
    - Decouple $\Lambda_{LNV}$ from heavy neutrino mass



# Problems of Naïve Seesaw

University College London

- Introduces high energy scale
- Right-handed neutrinos are singlets
  - Couple only via small mixture with active neutrinos
- Mechanism not testable with low energy observables
- Possible Solutions
  - SUSY Seesaw
    - Testable LFV effects from sleptons
  - "Bent" Seesaw mechanisms
    - Decouple $\Lambda_{LNV}$ from heavy neutrino mass
  - Left-Right symmetric models
    - Right-handed neutrinos couple with gauge strength to charged leptons



# Left-Right Symmetry

University College London

- Minimal Left-Right Symmetrical Model
  - Based on $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

    Pati & Salam '74
    Mohapatra & Senjanovic '75
  - Higgs Sector
    - Right-handed Triplet $\Delta_R$ $(SU(2)_R \times U(1)_{B-L} \to U(1)_Y)$
    - Left-handed Triplet $\Delta_L$
    - Bi-doublet $\phi$ $(SU(2)_L \times U(1)_Y \to U(1)_Q)$
  - Generate heavy masses $M_{N_R} \approx M_{W_R} \approx M_{Z_R} \approx \langle \Delta_R \rangle$
  - General Seesaw II Mechanism

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D^T & M_R \end{pmatrix}$$

  - Charged current weak interactions

$$J_{W_1}^{\mu-} = +\frac{g_L}{\sqrt{2}}\left(\bar{\nu}_i U_{li}^{LL} + \bar{N}_i^c U_{li}^{LR}\right)\gamma^\mu l_L + \frac{g_R}{\sqrt{2}}\sin\zeta_W\left(\bar{\nu}_i U_{li}^{RL} + \bar{N}_i^c U_{li}^{RR}\right)\gamma^\mu l_R$$

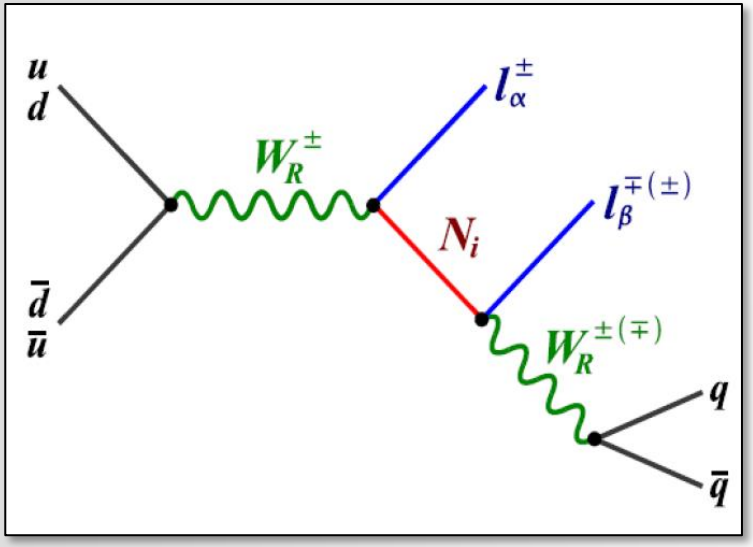
$$J_{W_2}^{\mu-} = -\frac{g_L}{\sqrt{2}}\sin\zeta_W\left(\bar{\nu}_i U_{li}^{LL} + \bar{N}_i^c U_{li}^{LR}\right)\gamma^\mu l_L + \frac{g_R}{\sqrt{2}}\left(\bar{\nu}_i U_{li}^{RL} + \bar{N}_i U_{li}^{RR}\right)\gamma^\mu l_R$$

Neglect LR Mixing

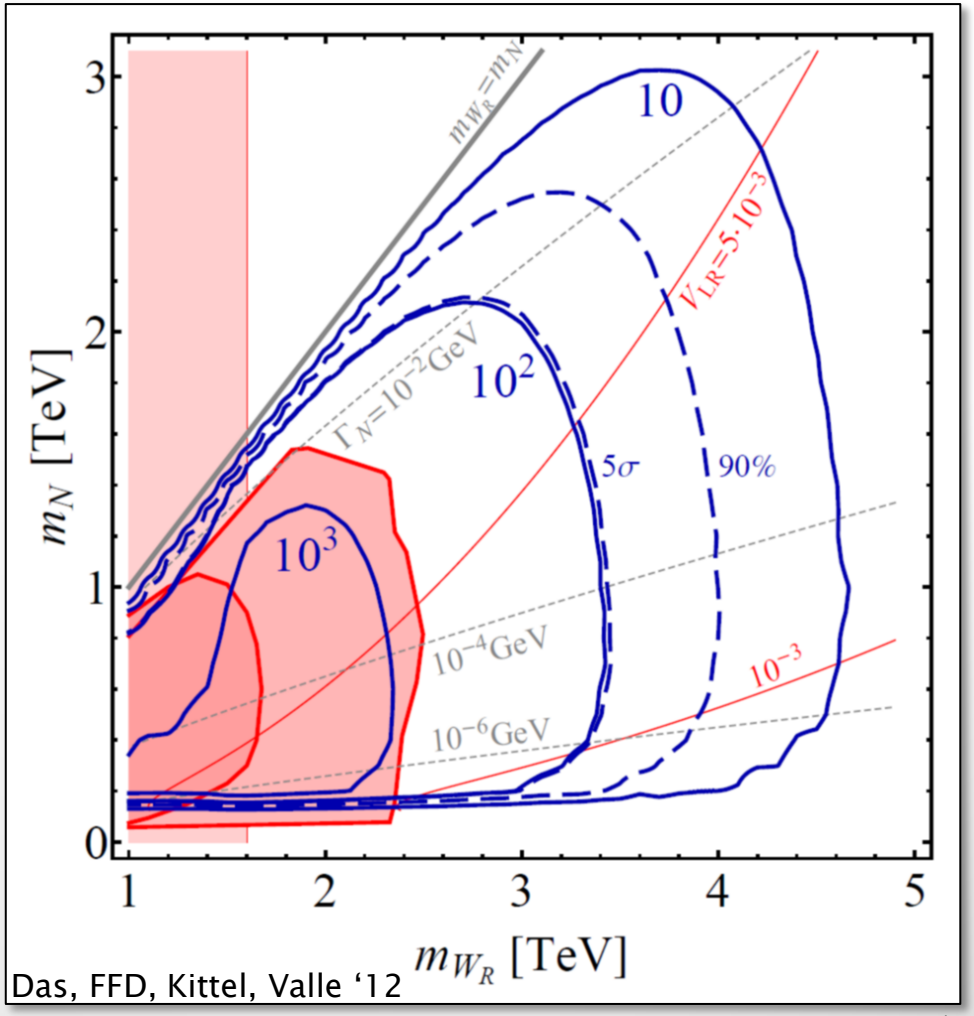
$$J_{W_L}^{\mu-} \approx \frac{g_L}{\sqrt{2}} U_{li}\bar{\nu}_i\gamma^\mu l_L$$

$$J_{W_R}^{\mu-} \approx \frac{g_R}{\sqrt{2}} V_{li}\bar{N}_i\gamma^\mu l_R$$

# LNV at LHC




- Monte Carlo Simulation (PROTOS)
- Main background $t\bar{t}$, $Z + \text{jets}$ (Pythia, Alpgen)
- Fast Detector Simulation (AcerDET)
- Selection Criteria
  - Number of jets $N_j > 2$
  - Number of isolated leptons $N_l = 2$
  - Invariant di-lepton mass $m_{ll} > 300\ \text{GeV}$
  - Total invariant mass $m_{lljj} > 1.5\ \text{TeV}$




Das, FFD, Kittel, Valle '12

LHC reach @ 14 TeV, 30 $\text{fb}^{-1}$
Opposite + Same Sign Leptons

# LNV at LHC

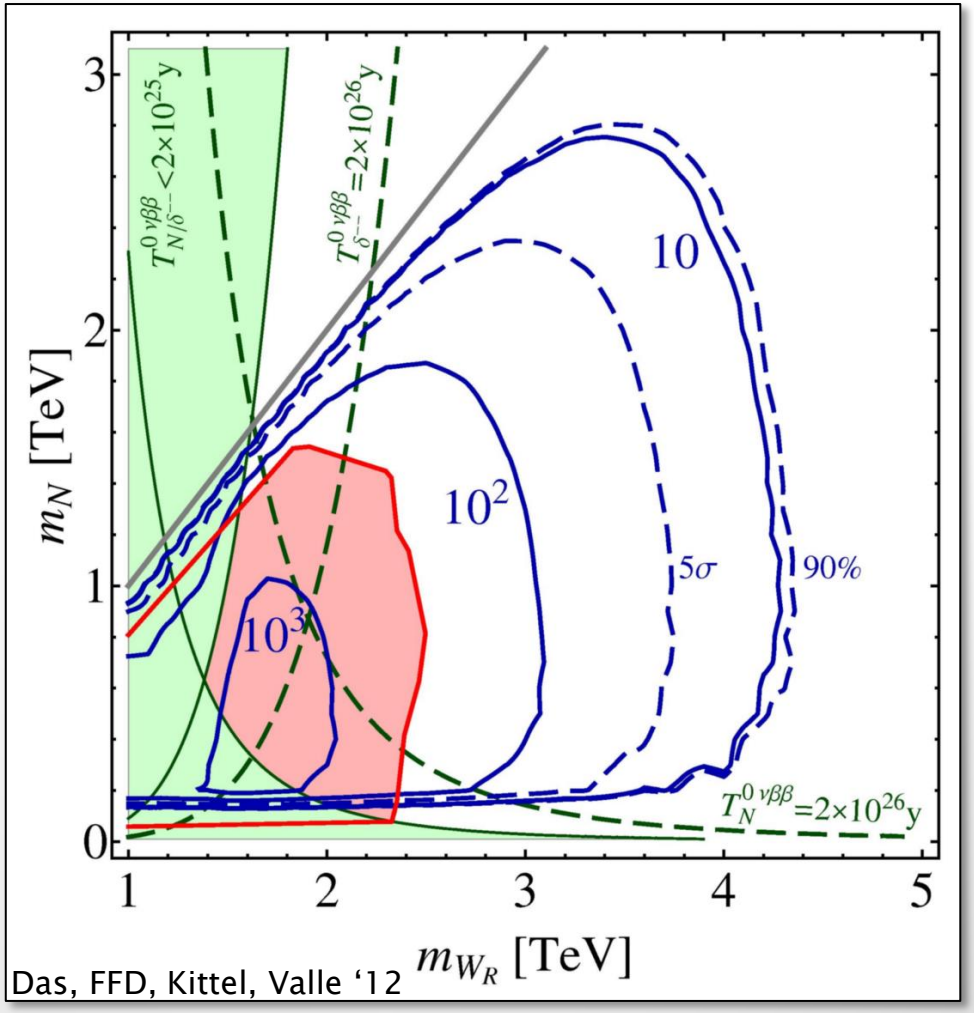
- Contributions to $0\nu\beta\beta$
  - Heavy Neutrinos

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{\left(U_{ei}^{RR}\right)^2}{M_{N_i}}$$

  - Triplet R-Higgs

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \frac{m_p}{M_{\Delta_R^{--}}^2} \sum_i \left(U_{ei}^{RR}\right)^2 M_{N_i}$$

  - LR-Mixing neglected



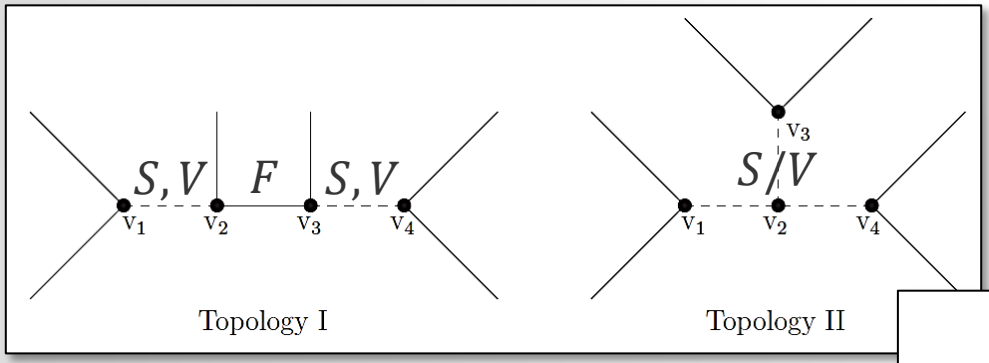

Das, FFD, Kittel, Valle '12

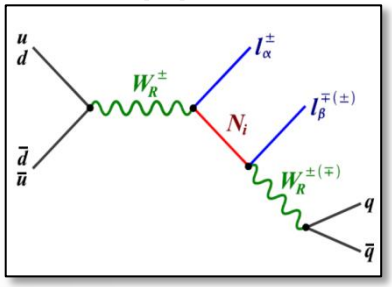
LHC reach @ 14 TeV, 30 $\mathrm{fb}^{-1}$
Same Sign Leptons

# General UV Completion

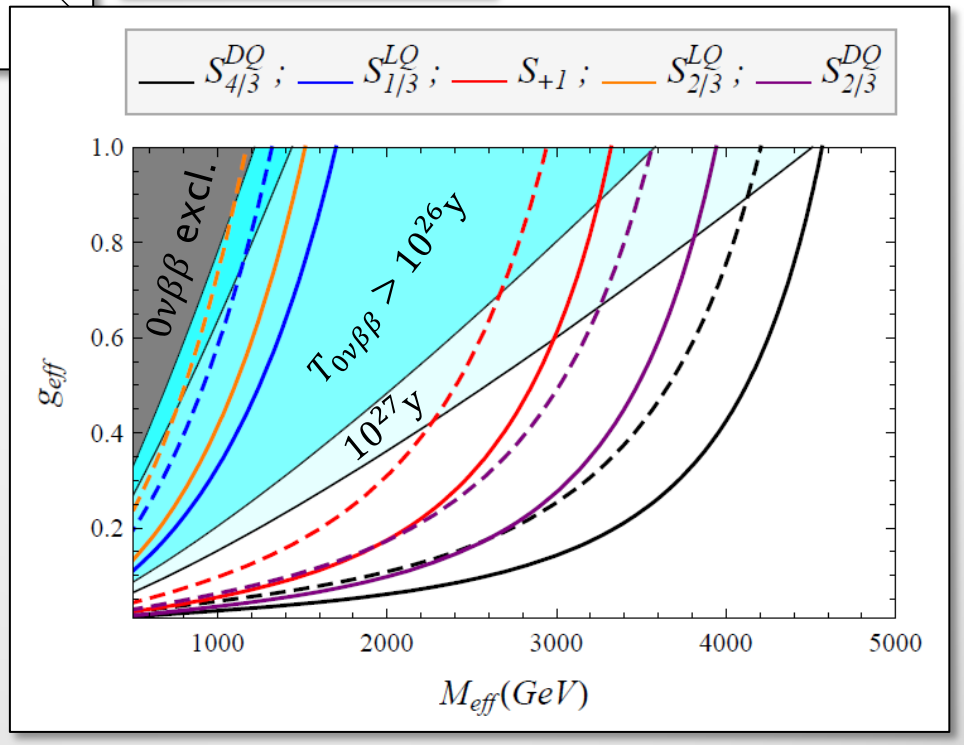
(Helo, Kovalenko, Hirsch, Pas '13)

- Generic Tree-level Topologies for $0\nu\beta\beta$ 9-dim Operator




- Sensitivity Comparison between $0\nu\beta\beta$ and LHC
  - LHC with $14\ \mathrm{TeV}, 300\ \mathrm{fb}^{-1}$
  - Heavy Resonance
  - LHC generally more sensitive if heavy particles can be produced on-shell



# Conclusion

University College London

- Neutrinos much lighter than other fermions
  - Strong experimental program to probe absolute mass
  - Dirac or Majorana? Lepton Number Violation?
- Standard $0\nu\beta\beta$ Majorana mass contribution well motivated
  - Unique Weinberg operator, Seesaw mechanism
  - But essentially untestable
- Need to probe alternative / extended LNV mechanisms
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - **Hope for the Best**
    - New LNV physics at the TeV scale
  - **Prepared for the Worst**
    - Only 5-dim operator from LNV physics at the GUT scale

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\text{yr} \rightarrow \Lambda_{LNV} \approx 1\ \text{TeV}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\text{yr} \rightarrow m_\nu \approx 0.1\ \text{eV}$$

- **Synergy with LHC**
  - LHC probes LNV at and above the TeV scale
  - LHC can be more sensitive than $0\nu\beta\beta$ if heavy particles mediating LNV are produced

$$\Lambda_{LNV} \approx 1 - 10\ \text{TeV}$$